

Arrivals of hitchhiking insect pests on international cargo aircraft at Miami International Airport

Barney P. Caton^{1,*}, Thomas T. Dobbs² & Charles F. Brodel²

¹*Plant Epidemiology and Risk Assessment Laboratory, United States Department of Agriculture (USDA), Animal and Plant Health Inspection Service (APHIS), Plant Protection and Quarantine (PPQ), Center for Plant Health Science and Technology, Raleigh, NC, 27606;* ²*USDA, APHIS, PPQ, Miami Inspection Station, Miami, FL;* **Author for correspondence (e-mail: barney.p.caton@aphis.usda.gov; fax: +919-855-7595)*

Received 18 December 2003; accepted in revised form 15 March 2005

Key words: contaminating pests, contamination, hitchhikers, introduction, non-indigenous pests, risk analysis

Abstract

In a study of hitchhiking or contaminating insect pests on international cargo aircraft at Miami International Airport from 1998 to 1999, it was found that contamination rates were greatest, 23%, on cargo flights from Central America and much lower, near 5%, on flights from all other regions. We reanalyzed the study data to test for associations between contaminated flights and factors such as season, cargo type, and time of departure (night or day), and developed probabilistic models for predicting insect pest arrivals by region and pest risk levels. Significant ($P < 0.05$) associations were detected between contaminated flights and (1) wet season flights from Central America, (2) flights carrying plant products and clothing or fabrics, and (3) flights departing at night from the country of origin. In Monte Carlo simulations, numbers of arriving mated insect pests were greatest for cargo flights from Central America, because of great contamination rates, and South America, because of the large volume of flights from there. Few insects arrived on flights from the Caribbean, and few high-risk insects arrived from anywhere. Although the likelihood of establishment in South Florida via this pathway could not be estimated, based upon arrivals the greatest threats were posed by moderate-risk insect pests on flights from Central and South America. Simulations indicated that switching to daytime departures only reduced pest arrivals by one-third. The simplest mechanism for pathway entry that explains the associations found is that insects entered aircraft randomly but sometimes remained because of the presence of certain cargo types. Hence, contamination rates were greater during the wet season because of greater abundance locally, and on nighttime flights because of greater abundance around lighted loading operations. Empty planes probably had no pests because pests had no access to holds. Thus, the best mitigation strategies for this pathway will likely be those that exclude insects from holds or reduce the attractiveness of night loading operations. Optimizing inspections based on associations is also possible but will be less effective for regions such as South America, with high flight volumes and low contamination rates. Comparisons to other pathways indicates the potential importance of hitchhikers on cargo aircraft at MIA.

Abbreviations: APHIS – Animal and Plant Health Inspection Service; CPHST – Center for Plant Health Science and Technology; C. Am. – Central America; CBP – Customs and Border Protection; DHS – Department of Homeland Security; MIA – Miami International Airport; PPQ – Plant Protection and Quarantine; S. Am. – South America; USDA – US Department of Agriculture

Introduction

Most introductions of non-indigenous plant pests into the United States are not by natural means but are human-mediated (National Research Council 2002). The means of introduction and potential establishment are called 'pathways,' defined as "any means that allows the entry or spread of a pest" (FAO 2002). Examples of human-mediated pathways include cargo, passengers, and conveyances entering the US (Office of Technology Assessment 1993). For example, introductions of insects to the US have historically been most ascribed to ships' ballast, introduced plants, and range extensions from countries north and south (National Research Council 2002). The risk of establishment via such pathways is increasing each year as global trade and travel increase (e.g., Simberloff 1997).

To help combat the threat, cargo, passengers, and conveyances are inspected at ports nationwide by thousands of officers of Customs and Border Protection (CBP) in the Department of Homeland Security (DHS) [formerly Animal and Plant Health Inspection Service (APHIS) officers in the US Department of Agriculture (USDA)]. Many pests are intercepted, and resources are normally directed to pathways where interceptions are highest, but the true risk of establishment of non-indigenous immigrant (not intentionally introduced) pests via different pathways is highly dynamic and often surrounded by a high level of uncertainty. Often, one of the missing pieces of information needed to understand and perhaps predict which species will become invasive is quantitative data about species' arrivals or immigration (National Research Council 2002).

Despite the best efforts of Federal and State agencies, non-indigenous species continue to be introduced into the US and to become established. By one estimate, 271 non-indigenous insect species were found to be established statewide in Florida from 1971 to 1991 (Frank and McCoy 1992). From 1992 to 2000, 64 newly established insect species, or 7.1 per year, were reported in the South Florida counties of Broward, Collier, Dade, Hendry, Lee, Monroe, and Palm Beach (Thomas 2000). Recognizing, however, that some of those introductions were natural

and only a portion were plant pests of concern is important.

International cargo aircraft are a potentially important pathway for the introduction of pests, especially when volume is considered. About 19,000 international cargo planes arrive per year at Miami International Airport (MIA), or ca. 52 planes per day (Quade 2003). Frank and McCoy (1995) reported that 85% of all imported plants arrive in the US via MIA. Past inspections of cargo aircraft by APHIS' Plant Protection and Quarantine (PPQ) officers had intercepted pests in holds (USDA-APHIS-PPQ 2004a), which may be either associated with the commodities on board, or be 'hitchhikers'. In standard terminology, hitchhikers are "contaminating pests" carried by but not infesting a commodity or conveyance (FAO 2002).

The cargo aircraft pathway has been little studied. Twenty years ago researchers found a very low contamination rate of 0.7% on all aircraft arriving in Trinidad, West Indies (Le Maitre and Chadee 1983). Moreover, 83% of the insects found were house flies (*Musca domestica*: Muscidae). Takahashi (1984) found a much greater contamination rate, 43%, for human-health related insects, but that was for passenger aircraft. We know of no other directed studies on cargo aircraft.

To evaluate the risk from hitchhiking pests on cargo aircraft at MIA, a study was conducted in 1998 and 1999 by the local Pest Risk Management Committee (PRMC) (PRMC 2000; Dobbs and Brodel 2004). Cargo holds of two aircraft per day were sampled for pests, which were identified when found. Based on the overall contamination rate of 10.5% the authors concluded that the risk of pest introductions from cargo aircraft was unacceptably great. The contamination rate on flights from Central America (C. Am.) was 23%, much greater than rates near 5% for flights from South America (S. Am.), the Caribbean, and all other regions. One-third of the insect pests were in the Scarabaeidae or Noctuidae families. The authors found that wet season flights from C. Am. were significantly more likely to be contaminated than dry season flights. They detected no significant associations between contaminated flights and three factors: (1) day or night time departure of the aircraft, for flights

from C. Am. only, (2) aircraft type, and (3) regulated or non-regulated cargo.

Our objective was to update and extend the analysis of the study data (PRMC 2000; Dobbs and Brodel 2004) to better understand the potential risk from pests on cargo aircraft. Slight corrections were made to the data. We tested for associations between contaminated flights and factors such as seasonality, day- or night-time departure, and cargo types. In addition, we developed probabilistic models that enabled predictions of annual insect pest arrivals at MIA by region and pest risk class.

Quantitative risk analysis explicitly accounts for variability in model parameters in order to determine the probability distribution of possible outcomes (Vose 2000). Parameters in probabilistic models are represented by probability distribution functions rather than point estimates. Model calculations use input values randomly sampled from those distributions over thousands of iterations. Probabilistic modeling offers several advantages to empirical analysis. First, the model accounts for uncertainty in parameter values in such models, and generates output as likelihoods or confidence ranges. Most important, a model links empirical information about different processes (e.g., no. of contaminated flights, no. of pests per flight, no. of adults, etc.) to simulate the entire system of interest. That enables us to ask and answer more complex, specific questions, such as, "What is the probability that at least one moderate-risk female insect pest will arrive per day from region *X*?" The analysis required very few assumptions because most distributions could be specified from the study data.

Methods

Study methodology and data

Full descriptions of the methodology are found in PRMC (2000) and Dobbs and Brodel (2004). Briefly, the project ran from September 1, 1998, to August 31, 1999. Two aircraft per day were randomly chosen from the full 24 h period of arrivals. Specially-trained and equipped APHIS-PPQ officers conducted the aircraft inspections. Officers inspected crew areas and

cargo holds, and were present from when holds were first opened until all cargo was offloaded. The surfaces of palletized cargo and all empty compartments in the hold were all intensively searched for hitchhiking organisms. Based on 75 randomly sampled inspection reports, the mean duration of inspections was 116 min (standard deviation(SD)=39 min).

Pests found were identified to the most specific taxon possible, and classified according to PPQ guidelines as quarantine-significant or not (Dobbs and Brodel 2004). 'Quarantine pest,' as defined by the International Plant Protection Convention (IPPC), means "a pest of potential economic importance to the area endangered thereby and not yet present there, or present but not widely distributed and being officially controlled" (FAO 2002). Possible taxa include phytophagous insects, mites, or mollusks, plant-infecting pathogens, or weeds. Generic or family level taxa are included if they contain potentially quarantine-significant species. Lists are maintained by USDA-APHIS-PPQ. The basic approach matched Stanaway et al. (2001) in Australia, who studied "quarantinable" insects in sea cargo containers.

Data were number of aircraft sampled, number of contaminated flights, and numbers and identifications of insect pests (Dobbs and Brodel 2004). We excluded one case of a (non-insect) disease found on citrus in the crew cabin, for a total of 72 contaminated flights. Information also included time of departure from origin, type of aircraft, and whether the cargo aboard was regulated by PPQ or not. Origins were grouped by regions as C. Am., S. Am., Caribbean, and all others ('Other') (Appendix A). For simplicity we grouped Mexico with countries in C. Am., as before (Dobbs and Brodel 2004). Pest interception records were verified in the Port Information Network (PIN309) database maintained by APHIS-PPQ. After corrections the total number of insects intercepted increased by seven, on one less flight than in Dobbs and Brodel (2004). The number of families was unchanged.

Contamination rates and intercepted insect pests

To verify previous findings for corrected data we tested for regional differences in numbers of

planes sampled, numbers of contaminated planes, and contamination rates by ANOVA. Contamination rates were the number of contaminated flights divided by the total number of flights. Levene's test of homogeneity of variance and residual analysis were used to verify that the data were normally distributed (SAS Institute 2001). Pairwise comparisons of means were done with Tukey's correction to hold overall error at $\alpha=0.05$ (as for all ANOVAs below unless otherwise specified). Numbers of contaminated planes were not normally distributed ($P<0.01$) so were analyzed using a one-way nonparametric test. Country-specific contamination rates were not analyzed here because sample sizes were usually too small.

We assigned insect pest risk ratings of low, moderate, or high to all intercepted pests, using guidelines adapted from those used for pests on cut flowers (Program and Policy Development (PPD) 1983). Ratings were given for the most specific taxa possible, using primary and secondary sources (not shown). In general, high-risk ratings were given for pests expected to cause serious damage in any ecosystem with at least a moderate risk of colonization potential, and identified at least to genus. Low-risk ratings were given to pests with less specific taxonomic information but expected to be a plant pest with wide distribution in the US, or to have low potential to either colonize or cause serious damage. Moderate-risk ratings were given to pests not falling into the other two risk rating classes. Ratings only considered taxa in the three main regions of interest, rather than worldwide.

Association tests

We tested or retested for associations between contaminated flights and aircraft departure times, seasons, and cargo types. Frequency table analyses ("Proc Freq") were used for association tests (SAS Institute 2001). Tests of interactions, such as for regions, controlled for the relevant factors, which gave 2-by-2 frequency tables for each factor class (e.g., one table per region or taxonomic group). Exact tests were always used to determine significance. The likelihood ratio χ^2 test (called the "G-test" in Dobbs and Brodel 2004) was usually applicable but Fisher's exact

test was used if any cell counts equaled zero (SAS Institute 2001). Strengths of associations were assessed using Cramer's V, where values <0.1 indicate weak relationships. We note that for all 2-by-2 χ^2 tables, $df=1$.

Seasonality

We first tested for monthly trends in interceptions using an unbalanced ANOVA (GLM) with the factors month, region, and month \times region. For significant results, interception and flight data were further analyzed to determine the likely cause(s) of seasonality. We tested for associations between contaminated flights and climatic seasons, the most notable of which were the dry and wet seasons in C. Am. For most countries in C. Am. the wet season is from May to October, although start and end dates may vary from year to year (Gomez et al. 2003). The wet season for Mexico was only 4 months long, from June to September. Flights were coded as being in either a dry- or wet-season month, which were categorized by country based on historical averages (World Meteorological Organization 2003).

Aircraft departure times

Departure times in Greenwich Mean Time were converted to local time at origin but were not adjusted for daylight savings time because it is used by very few tropical and equatorial countries. Flights were coded as either daytime or nighttime departures, with daylight hours defined as 7:00 am–7:00 pm. Because of some missing times, $n=678$. We tested associations over all flights and also for taxa known to be either nocturnal or attracted to light: Chrysomelidae (e.g., Clark 1997), Geometridae, Noctuidae (Borror et al. 1989), Scarabaeidae (e.g., Montoya et al. 1994), and the suborder Auchenorrhyncha, which includes the intercepted families Cercopidae, Cicadellidae, Cixiidae, and Nogodinidae. We also tested for just the Cicadoidea superfamily, which contains only two of those four families, Cercopidae and Cicadellidae.

Cargo types

Information about cargo types was taken from manifests. Only 647 of 702 manifests were available: the others were either not submitted or not kept. Some details, such as the kind of fruit,

were often not reported. Flights were coded by the presence or absence of cargo in categories such as machinery, clothing, electronics, live plants, fruit, vegetables, empty, etc. Broad categories, such as 'plant products,' 'animals or animal products,' and 'dry goods,' were used in initial tests. We also tested for significance of cargo types within each region.

Probabilistic model analyses

Simulation settings

The Monte Carlo simulation method was used, as is typical in quantitative risk analysis. Simulations were done with @Risk ver. 4.5.2-Professional (© 2002, Palisade Corporation, 31 Decker Road, Newfield, NY 14867), a Microsoft Excel add-in. Simulation settings were as follows: number of iterations=10,000; sampling type=Latin hypercube; and random seed=101. That number of iterations was chosen to adequately sample input distributions and populate output distributions. Latin hypercube is a stratified sampling method that usually better represents input distributions than simple random sampling. Specifying a random seed allows results to be exactly replicated in later simulations.

Probabilities of arrivals of adult female insect pests

The base model estimated annual numbers of arriving contaminated flights (F_{contam}), total insect pests (N_{tot}), and adult females by region ($N_{\text{♀-REG}}$) (Figure 1; Appendix B). The first inputs were annual flights by region ($F_{\text{tot-REG}}$), which were distributions output from a submodel (not shown). Those were based on MIA data for annual international cargo landings (Quade 2003). Regional proportions were estimated from annual freight tonnages from 1994 to 2001 (Bureau of Transportation Statistics 2003). The distributions were specified in histograms with min value, max value, and p values for each interval, with values rounded to the nearest integer. We assumed that the probabilities of flights from C. Am. being in the wet or dry season were equal (see below). This is a binomial process: n independent trials, each with a constant probability p of success, or binomial(n, p) (e.g., Vose 2000).

Hence, the wet season value was binomial ($F_{\text{tot-CA}}, 0.5$), and the dry season value was the difference from $F_{\text{tot-CA}}$.

Regional values of F_{contam} were modeled as follows:

$$F_{\text{contam-REG}} = F_{\text{tot-REG}} \times p_{\text{contam-REG}} \quad (1)$$

where $p_{\text{contam-REG}}$ is the empirical probability of contamination by region. For a binomial process (see above), a beta distribution estimates p from the known numbers of successes (s , empirical number of contaminated flights) and trials (n , total flights inspected), as beta($s + 1, n - s + 1$) (e.g., Vose 2000). Numbers of contaminated flights per month were $F_{\text{contam-REG}}$ divided by 12, or by 6 for the C. Am. seasons.

The number of insects arriving on contaminated flights by region ($N_{\text{tot-REG}}$; V3 in Figure 1) was estimated using the Central Limit Theorem, which states that for large n (usually $n \geq 30$), the sums of n independently sampled values are approximately normally distributed with mean = μ and variance = σ/\sqrt{n} (Vose 2000). Means ($X_{\text{bar-REG}}$) and standard deviations (SD_{REG}) for pests per flight by region and season were calculated from non-zero values. The general equation for $N_{\text{tot-REG}}$ was as follows (Vose 2003):

$$N_{\text{tot-REG}} = \text{normal}(F_{\text{contam-REG}} \times X_{\text{bar-REG}}, \sqrt{F_{\text{contam-REG}} \times SD_{\text{REG}}}) \quad (2)$$

where $N_{\text{tot-REG}}$ was rounded to the nearest integer.

Numbers of arriving adult insects per year by region ($N_{\text{adult-REG}}$; V4 in Figure 1) depended on $N_{\text{tot-REG}}$ and the probability of being an adult (p_{adult}) as follows:

$$N_{\text{adult-REG}} = N_{\text{tot-REG}} \times p_{\text{adult}} \quad (3)$$

where p_{adult} was estimated empirically as a beta distribution (see above) with s =number of adult insects=156 and n =total insect pests intercepted=158.

Numbers of females by region ($N_{\text{♀-REG}}$; V5 in Figure 1) were estimated as binomial ($N_{\text{adult-REG}}, p_{\text{♀}}$) where $p_{\text{♀}}$ =probability of being female=0.5. Means per month or day were derived by dividing $N_{\text{♀-REG}}$ by either 12 or 365. Means for

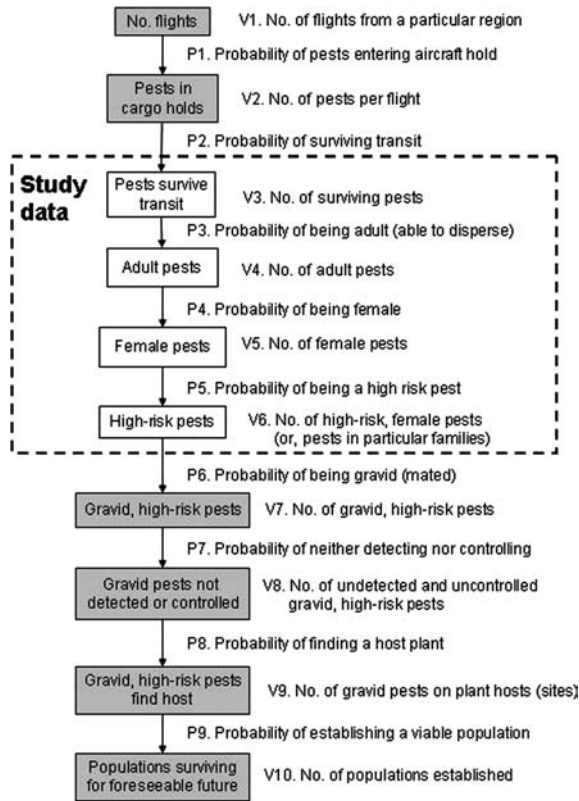


Figure 1. Probabilistic analysis of the arrival and establishment of insect pests on cargo aircraft to Miami International Airport. Boxes are variables (V#) and arrows are probabilities (P#). Processes explicitly studied were those within the dashed box. Except for V1, shaded boxes could not be estimated.

female pests per contaminated flight were $N_{\varphi-REG}$ divided by $F_{contam-REG}$, and means per flight (total) were $N_{\varphi-REG}$ divided by $F_{tot-REG}$. Results for $N_{\varphi-REG}$ were used as inputs in some subsequent models.

Probabilities of arrivals by risk class or taxa

Numbers of arrivals of females in particular risk rating classes, N_{class} (V6 in Figure 1), or families, N_{fam} , were estimated based on empirical frequencies. Because two insects were not identified to family level, $n=154$ adults. The probabilities of newly arriving pests being in particular families (p_{fam}) or risk rating classes (p_{class}) were estimated using the beta distribution, and constraining the sum of probabilities to 1.0 using multivariate Dirichlet distributions (Vose 2003). In general, estimates were as follows (shown for risk classes):

$$N_{class-REG} = N_{\varphi-REG} \times p_{class-REG} \quad (4)$$

where 'class' is low, moderate, or high. The equation for N_{fam} had the same form but used $p_{fam-REG}$. The sum of N_{fam} or N_{class} values within a region were constrained to $N_{\varphi-REG}$ using multinomial distributions (Olkin et al. 1994).

The formal analysis of insect pest arrivals ended here because little or no data were available about subsequent variables related to establishment: inspection efficiency (V7 in Figure 1), the likelihoods of both finding a host and having offspring survive to the next generation (V8 and V9), and the associated probabilities (P6–P8).

Summarizing, assumptions made in the model were as follows: (1) $p_{\varphi}=0.5$, (2) the chances of wet and dry season flights from Central America were equal, and (3) Central Limit Theorem assumptions were met in predictions of N_{tot} .

Threshold probabilities of establishment

The probability of an insect pest population establishing in South Florida via this pathway is p_{estab} , which is unknown. The number of insect populations establishing per year (N_{estab}) depends on N ($=N_{\varphi}$) and p ($=p_{estab}$) as we have seen before (e.g., Equation 4). We do not have enough information from this study to estimate N_{estab} , but to evaluate relative likelihoods one can assume $N_{estab-REG}=1$, and rearrange the basic equation to give:

$$p_{crit-REG} = N_{estab-REG}/N_{\varphi-REG} = 1/N_{\varphi-REG} \quad (5)$$

where $p_{crit-REG}$ is the minimum threshold or critical probability by region for at least one pest population to successfully establish. As $N_{\varphi-REG}$ increases, $p_{crit-REG}$ decreases or becomes more easily exceeded, i.e., the likelihood of establishment is proportional to propagule pressure. We stress that this does not estimate the actual p_{estab} .

Mitigation by changing departure times

We tested in simulations the mitigation effect of switching to daytime departures of aircraft. F_{tot} was estimated as in the flight submodel. The probability of nighttime departure (p_N) was 0.49 (332/678). The number of nighttime flights (F_N)

Table 1. Summary of flight and interception data by region and country. Flights sampled, contaminated, percentage of flights contaminated, and total number of reportable insect pests found on international cargo aircraft at Miami International Airport from 1998 to 1999^a.

Region	Origin	No. flights			No. pests
		Contaminated	Total	Percentage ^b	
Caribbean	Antigua	0	2	0.0	0
	Aruba	0	1	0.0	0
	Bahamas	0	42	0.0	0
	Barbados	0	1	0.0	0
	Cayman Islands	0	3	0.0	0
	Cuba	0	1	0.0	0
	Dominica	0	2	0.0	0
	Dominican Republic	1	34	2.9	2
	Grenada	0	3	0.0	0
	Haiti	2	11	18.2	2
	Jamaica	1	12	8.3	1
	Puerto Rico	0	1	0.0	0
	St. Kitts	0	4	0.0	0
	St. Lucia	0	3	0.0	0
	St. Vincent	0	1	0.0	0
	Turks and Caicos	0	1	0.0	0
Subtotals		4	122	1.8	5
Central America	Costa Rica	12	44	27.2	32
	El Salvador	4	16	25.0	25
	Guatemala	12	44	27.3	28
	Honduras	8	33	24.2	19
	Mexico	4	33	12.1	7
	Nicaragua	4	9	44.4	10
	Panama	4	28	14.3	4
Subtotals		48	207	23.1	125
South America	Argentina	0	6	0.0	0
	Bolivia	0	4	0.0	0
	Brazil	0	29	0.0	0
	Chile	0	45	0.0	0
	Colombia	8	155	5.2	11
	Ecuador	7	44	15.9	11
	Peru	1	16	6.3	1
	Trinidad	2	17	11.8	3
	Uruguay	0	1	0.0	0
	Venezuela	1	28	3.6	1
Subtotals		19	345	5.5	27
Other	Canada	1	3	33.3	1
	China	0	1	0.0	0
	France	0	3	0.0	0
	Luxembourg	0	4	0.0	0
	Netherlands	0	10	0.0	0
	Spain	0	5	0.0	0
	Taiwan	0	2	0.0	0
Subtotals		1	28	4.8	1
Grand totals		72	702	10.3	158

^aOnly insect pests were included here.

^bPercentages = (contaminated flights/total flights) × 100. Subtotals for percentages were calculated for data from all countries. In PRMC (2000) mean contamination rates were only calculated for countries with non-zero values.

in the baseline (unmitigated) scenario was estimated as $\text{binomial}(F_{\text{tot}}, p_N)$. The number of daytime flights (F_D) was $F_{\text{tot}} - F_N$. In two mitigation scenarios p_N values were reduced by 75% to 0.123, and by 90% to 0.049.

Numbers of contaminated nighttime ($F_{N\text{-contam}}$) or daytime ($F_{D\text{-contam}}$) flights were estimated as in Equation (1), using day- or nighttime data over all regions. Hence, the probability that a nighttime flight was contaminated ($p_{N\text{-contam}}$) used $s=46$, $n=286$, and that for daytime flights ($p_{D\text{-contam}}$) used $s=24$, and $n=322$. F_{contam} was the sum of $F_{N\text{-contam}}$ and $F_{D\text{-contam}}$, and the overall contamination rate was $F_{\text{contam}}/F_{\text{tot}}$.

Results

Intercepted pests and pest risk ratings

The most intercepted taxa of hitchhikers were discussed in PRMC (2000) and Dobbs and Brodel (2004). After slight corrections here, 158 total insect pests in 33 families were intercepted (Table 1 and Appendix A). Taxa were often not identified below the family level, which usually meant lower pest risk ratings. The two most intercepted families were Scarabaeidae and Noctuidae, and the most intercepted genus was

Gryllus (Gryllidae) (Table 2). The mean probability of an insect pest being in the six most-intercepted families combined (i.e., beta with $s=103$) was 0.66. Notably, four of those families were either nocturnal or attracted to light: Chrysomelidae, Scarabaeidae, Noctuidae, and Geometridae. Tephritidae or fruit flies (e.g., *Anastrepha* spp. or *Bactrocera* spp.), which probably most threaten agriculture in Florida (e.g., Knapp 1988), were not detected on cargo aircraft during the study. First interceptions of pest taxa on cargo airplanes either at MIA or for the entire US indicated that cargo aircraft are a novel pathway for some insects (Dobbs and Brodel 2004; Appendix A).

Most contaminated flights had only one or two insect pests (see Dobbs and Brodel 2004). Numbers of pests per contaminated flight were greatest for C. Am., mostly because more flights had from 3 to 7 pests. Two or more pests in the same family were only found on 20 contaminated flights (Figure 2). The probability of that occurring was 0.14, while the probability of having 3 or more pests in one family on one flight was only 0.06.

Nearly all insects found were adults, with $p_{\text{adult}}=0.98$ (156/158). Thus, few immature insects entered the pathway. The two immatures found were a tettigoniid nymph, and a larva of

Table 2. Numbers and common names of adult insect pests found on cargo aircraft at Miami International Airport, by family and by most frequent genus or genera, and the mean probabilities of a pest being in a particular family (p_{Fam} ; see text).

Family	Common name	No.	p_{Fam}	Genus	No.
Scarabaeidae	Scarab beetles	30	0.20	(tie) <i>Anomala</i>	7
				<i>Phyllophaga</i>	7
Noctuidae	Noctuid moths	26	0.17	spp.	18
Chrysomelidae	Leaf beetles	15	0.10	<i>Colaspis</i>	3
Gryllidae	Crickets	13	0.09	<i>Gryllus</i>	11
Geometridae	Inchworms, geometers	11	0.08	spp.	10
Cicadellidae	Leaf hoppers	8	0.06	spp.	2
Miridae	Plant or leaf bugs	5	0.03	<i>Tropidosteptes</i>	2
Curculionidae	Weevils, snout beetles	5	0.03	<i>Conotrachelus</i>	2
Pyrilidae ^a	Snout or grass moths	4	0.03	spp.	4
Tettigoniidae	Grasshoppers, katydids	4	0.03	spp.	2
Crambidae	Grass moths	3	0.02	spp.	2
Elateridae	Click beetles	3	0.02	<i>Conoderus</i>	3
Five with		2	0.02		
Fourteen with		1	0.01		

^aIncludes one pest interception with a designation of Pyraloidea.

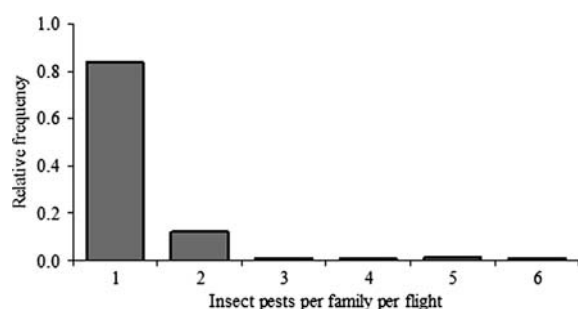


Figure 2. Insect pests intercepted per family per cargo aircraft flight at Miami International Airport.

the moth, *Crociosema aporema* (Walsingham) (Tortricidae). They probably dropped off cargo on those flights (Dobbs and Brodel 2004). Arriving adults likely pose a much greater threat than immature insects because they disperse much more easily and may include gravid females. In order to establish, immature insects need to escape the aircraft and airport environs, find a host, complete development, find a compatible mate, and reproduce. This seems very unlikely given their low mobility. Thus, establishment via this pathway is probably only likely for adult insect pests.

Insect pest interceptions were evenly split between moderate-risk pests and low-risk pests (Table 3). Five high-risk pests were also intercepted: *Conotrachelus* sp. (Curculionidae), *Copitarsia* sp. (Noctuidae), *Crociosema aporema*, and *Euethola bidentata* Burmeister (Scarabaeidae). Overall probabilities (unconstrained) for the next arrival to be either a low- or moderate-risk insect pest were similar, about 0.49, while that for a high-risk insect was much smaller at 0.04.

Probabilities of low- and moderate-risk insect pest arrivals on aircraft from C. Am. were about equal, $p \approx 0.5$ (Table 3). In contrast, insects from the Caribbean and S. Am. were more likely to be low risk. High-risk pests seemed most likely to arrive from the Caribbean but that simply reflected lower sample sizes and interceptions. High-risk pests were about twice as likely to come from S. Am. as from C. Am., but the overall likelihoods were low for both.

Pests on cargo aircraft by region

Significant differences by region were detected for numbers of planes sampled ($P < 0.05$) and contamination rates ($P < 0.01$), as well as numbers of flights with insects ($P < 0.01$ by Kruskal–Wallis). Thus, further analyses considered the different regions separately. The greatest flight contamination rate was for C. Am. Of all individual pests intercepted, 79% came from C. Am., 17% from S. Am., and only 3% from the Caribbean (Table 1). Only one pest was intercepted on cargo aircraft from any other origin, although the fewest flights came from those places. The greatest number of inspected planes were from S. Am. (Table 1), as expected because about two-thirds of all flights to Miami originate from there.

Pathway factors associated with contaminated flights

Seasonality

A significant month by region interaction ($P < 0.05$) was detected. Within regions that was only

Table 3. Numbers of insects intercepted (no.) by risk rating class within regions, and associated probabilities (p_{Class}). One interception of a low-risk pest on a flight from a different region ('Other') is not shown.

Region	Risk rating class	No.	p_{Class}
Central America	High risk	4	0.04
	Moderate risk	63	0.50
	Low risk	58	0.46
South America	High risk	1	0.07
	Moderate risk	11	0.40
	Low risk	15	0.53
Caribbean	High risk	0	0.13
	Moderate risk	2	0.38
	Low risk	3	0.50

significant for C. Am. (Figure 3). As mentioned above, countries in C. Am. are known for distinct dry and wet seasons. Wet season flights from C. Am. were significantly more likely to be contaminated than dry-season flights ($G=4.84$, $P < 0.03$, $V=0.15$): 69% of all contaminated flights originated in the wet season (Table 4). Moreover, 29% of all wet-season flights were contaminated, but only 16% of all dry-season flights.

Aircraft departure times

Over all regions, cargo flights departing at night were significantly more likely to be contaminated than daytime flights ($G=8.9$, $P < 0.01$, $V=0.11$), as 66% of all contaminated flights departed at night, and 16% of all nighttime flights were contaminated. In contrast, only 7% of daytime flights were contaminated. No significant associations were detected within regions ($P > 0.05$).

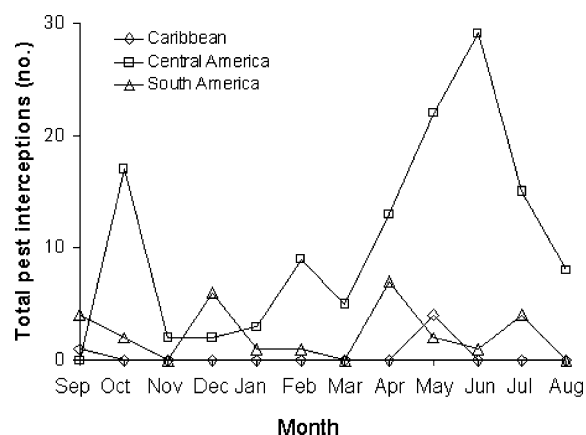


Figure 3. Numbers of insect pests intercepted by month at Miami International Airport from September 1, 1998, to August 31, 1999, on cargo aircraft from countries in three regions.

For nocturnal or light-attracted taxa, no significant association was detected for Auchenorrhyncha ($P > 0.05$). Over all regions, Cicadoidea ($G=6.2$, $P < 0.05$, $V=0.09$), Noctuidae ($G=5.5$, $P < 0.05$, $V=0.09$), and Scarabaeidae ($G=7.4$, $P < 0.01$, $V=0.10$) were all more likely to be found on nighttime flights than daytime flights (Table 5). Eight of nine (89%) flights with Cicadoidea departed at night. Nighttime flights made up 76% of all flights with Noctuidae, and 79% of all flights with Scarabaeidae. No significant within-region associations were found for any of those taxa ($P > 0.05$), but for the three groups of taxa combined, an association was found for flights from C. Am. ($G=10.0$, $P < 0.01$, $V=0.21$). Of those nighttime flights, 27% were contaminated by at least one of the three (Table 5).

Types of cargo

At least one insect pest was found on flights with every type of cargo recorded except for leather goods ($n=17$) and empty planes ($n=51$). A significant negative association was detected for empty aircraft (Fisher's exact $P < 0.01$, $V=-0.096$), and significant positive associations were detected for all plant products ($G=4.1$, $P < 0.05$, $V=0.075$), and clothing (plus fabrics) ($G=22.8$, $P < 0.0001$, $V=0.18$). Some associations were weak. Significant associations were not detected ($P > 0.05$) for several cargo types, such as animals (live or products), consolidated goods, tobacco, machinery, household goods, handicrafts, toiletries, electronics, and personal effects. The presence of insect pests in those cargo types appeared to be random.

Within plants or plant products, significant associations were detected for live plants ($G=15.2$, $P < 0.0001$, $V=0.17$) and vegetables ($G=7.7$, $P < 0.01$, $V=0.11$) over all regions but

Table 4. Frequency table, including relative frequencies and expected values (rounded to nearest integer), for the relationship between contaminated flights and dry or wet season flights of cargo aircraft from Central America to MIA.

	Frequency		Totals	Relative frequency		Expected value	
	Dry	Wet		Dry	Wet	Dry	Wet
Contaminated	15	33	48	0.07	0.16	22	26
Not contaminated	78	81	159	0.38	0.39	71	88
Totals	93	114	207	—	—	—	—

Table 5. Frequency table, with relative frequencies and expected values, for the associations between contaminated (+ or –) flights and night and day departure times of cargo aircraft to MIA. Tests^a were for all insects or the taxa Noctuidae, Scarabaeidae, and Cicadoidea, and the combination of those groups.

Group	Contaminated	Frequency		Relative frequency ^b		Expected value ^c	
		Day	Night	Day	Night	Day	Night
All insects	+	24	46	0.03	0.07	36	34
	–	322	286	0.48	0.42	310	298
Noctuidae	+	4	13	0.01	0.02	9	8
	–	341	319	0.50	0.47	336	324
Scarabaeidae	+	4	15	0.01	0.02	10	9
	–	341	317	0.50	0.47	335	323
Cicadoidea	+	1	8	0.001	0.01	5	4
	–	344	324	0.51	0.48	340	328
Families above	+	4	28	0.01	0.14	11	21
(C. Am. only)	–	67	102	0.33	0.51	60	109

^aAll listed associations were significant by exact association tests ($P < 0.05$; see text).

^b $n = 677$ for flights over all regions. $n = 202$ for Central American (C. Am.) flights.

^cValues were rounded to the nearest integer.

not for seeds, cut flowers, or fruit ($P > 0.05$). Pests were found on 28% of all flights with live plants; 86% of those shipments came from C. Am. Within regions, the association with all plant products only remained significant for flights from C. Am. ($G=7.4$, $P < 0.01$, $V=0.19$). Also on C. Am. flights, 50% of flights with herbs had

insect pests ($G=5.8$, $P < 0.05$, $V=0.18$), and on 35% of flights with vegetables ($G=5.0$, $P < 0.05$, $V=0.16$). Despite these associations, no evidence indicated that insect pests arrived on board with cargo. Two primary reasons for that were that (1) insect taxa were often not specific enough to identify potential host plants, and (2) varieties of plant

Table 6. Simulated arrivals of female insect pests at Miami in three risk classes from three regions, with the estimated minimum threshold probability for establishment per year (p_{crit}). Summary data are means and the 5th and 95th percentiles (Pctl_x) of the distributions.

Region	Season	Pest risk	Female insects				$p_{\text{crit}}^{\text{a}}$
			Per month		Per year		
			Mean	Pctl ₅	Pctl ₉₅	Mean	
Caribbean	—	Low	3.5	1.1	7.3	41.8	0.024
		Moderate	1.4	0.2	3.6	16.7	0.060
		High	0.7	0.0	2.3	8.4	0.120
Central America	Dry	Low	24.4	14.8	36.3		
		Moderate	22.5	13.3	33.5		
		High	0.4	0.0	1.3		
Central America	Wet	Low	55.7	38.2	76.0		
		Moderate	51.3	35.2	70.2		
		High	0.9	0.0	2.8		
Central America	Total	Low				480.5	0.002
		Moderate				442.8	0.002
		High				7.5	0.133
South America	—	Low	17.8	9.7	27.9	213.6	0.005
		Moderate	20.5	11.6	31.5	246.3	0.004
		High	2.7	0.4	6.7	32.8	0.031

^a $p_{crit} = 1/\text{mean mated insects per year}$. Greater values indicate *less* chance of establishment. See text for more information.

products, such as herbs and vegetables, were often unknown.

Significant associations were probably found here but not in Dobbs and Brodel (2004) because we used added detail about cargo types and tested all data, not just data for C. Am.

Predicted arrivals of hitchhiking insect pests

Arrivals of mated insects by region

Few female insect pests per year (N_{φ}) arrived in Miami from either the Caribbean or Other regions (Table 6). Mean $N_{\varphi\text{-Carib}}$ was 57.9 (5th percentile (Pctl_5)=19, 95th percentile (Pctl_{95})=121) and that for other regions was 41.7 (Pctl_5 =7, Pctl_{95} =103). Mean numbers of arrivals per flight were 0.025 for the Caribbean and 0.03 for Other regions. Those equaled 1 female pest arrival per 40 flights from the Caribbean or 1 per 33 flights from Other regions.

By comparison, $N_{\varphi\text{-SA}}$ and $N_{\varphi\text{-CA}}$ were much greater. Mean $N_{\varphi\text{-SA}}$ was 487 (Pctl_5 =315, Pctl_{95} =692), or 40.6 female pests per month and 1.3 per day. Mean $N_{\varphi\text{-CA}}$ was 926 (Pctl_5 =696, Pctl_{95} =1189), with a mean of 649 (Pctl_5 =465, Pctl_{95} =859) arriving in the wet season and a mean of 277 (Pctl_5 =170, Pctl_{95} =403) in the dry season. That equaled 108.2 arrivals per month (3.6 per day) in the wet season and 46.1 arrivals per month (1.5 per day) in the dry season. Mean $N_{\varphi\text{-SA}}$ per flight was low, however: only 0.04 insects per flight, or 1 pest arrival every 25 flights. In contrast, mean $N_{\varphi\text{-CA}}$ per flight was 0.4 in the wet season, or 1 female every 2.5 flights on average, and 0.17 in the dry season, or 1 female adult every 5.9 flights.

Arrivals by risk class

The greatest numbers of low- and moderate-risk female pests arrived on flights from C. Am., especially during the wet season (Figure 4a, b and c). Mean $N_{\varphi\text{-CA}}$ per month on wet season flights from C. Am. were twice as great for both low- and moderate-risk mated insects than for mean arrivals from either C. Am. in the dry season or the other two regions (Table 6).

The probability of arrival of at least 1 high-risk female pest per month was 0.81 for flights from S. Am., but 0.29 for wet-season flights from C. Am. and 0.08 during the dry season. In con-

trast, the probability of 30 or more moderate-risk pest arrivals per month (i.e., about 1 per day on average) from C. Am. was 0.99 in the wet season, but only 0.12 in the dry season and 0.07 from S. Am. The probability of at least 1 moderate-risk pest per month on flights from the Caribbean was 0.53 but that for three or more was only 0.08. For C. Am. flights the probability of 30 or more low-risk insects per month was 0.997 during the wet season but only 0.19 during the dry season. The same probability was 0.03 for year-round flights from S. Am.

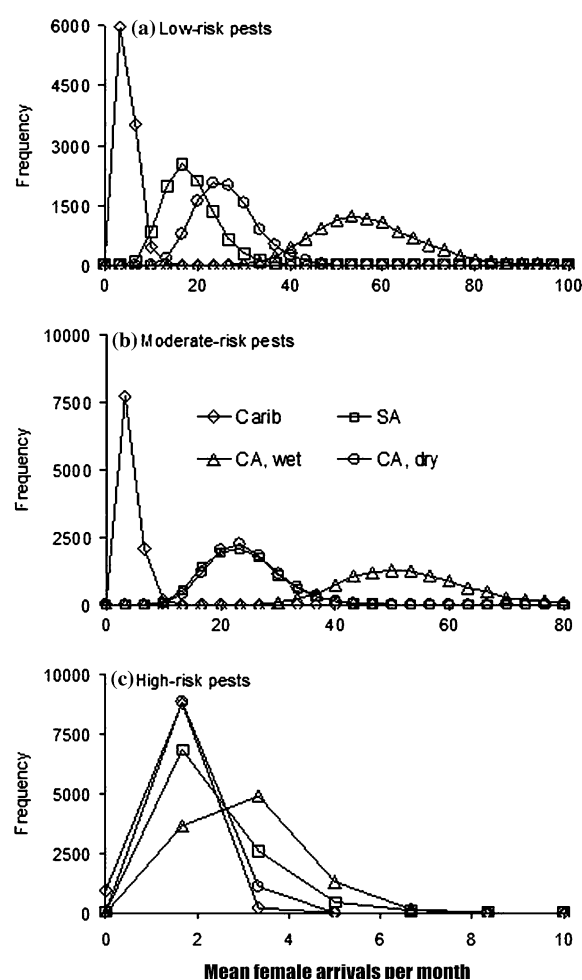


Figure 4. Distributions of model results for arrivals of (a) low-risk, (b) moderate-risk, or (c) high-risk female insect pests per month on cargo aircraft at Miami International Airport from the Caribbean (Carib), South America (S. Am.), and Central America in the dry (C. Am., dry) and wet (C. Am., wet) seasons.

Table 7. Simulation results for the mitigation effects of decreasing the number of night-departing international cargo flights per year to Miami from all regions.

Reduction (%)	Annual flights (no.)					Change ^a (%)	Contamination rate ^b (%)
	Mean total		Mean contaminated				
	Night	Day	Night	Day	Total		
0	9226	9615	1506	742	2248	–	11.9
75	2307	16535	376	1276	1652	–26.5	8.8
90	923	17919	151	1383	1533	–31.8	8.1

^aCalculated as percent change = [(new total/baseline total) – 1] × 100.

^bContamination rate = (contaminated flights/total flights) × 100.

Estimated threshold establishment probabilities

The greatest mean N_{φ} were for low- and moderate-risk insects from C. Am., which gave p_{crit} values of 0.002 (Table 6). In other words, for either of those groups we expect at least one population to establish via this pathway if $p_{\text{estab}} = p_{\text{crit}} = 0.002$. For low- and moderate-risk pests from S. Am., p_{crit} values were double. In contrast, mean high-risk N_{φ} from C. Am. and the Caribbean were only 7 or 8, and p_{crit} was 0.12 or 0.13. In other words, so few pests in those categories arrived that unless p_{estab} is very great, they will not be able to successfully establish. Values of p_{crit} were moderate, ca. 0.05, for low- and moderate-risk pests from the Caribbean, and high-risk pests from S. Am. (Table 6).

Mitigation by altering departure times

Switching to daytime departures of flights significantly – but not overwhelmingly – decreased F_{contam} (Table 7). A 75% reduction in F_N reduced F_{contam} by 27%, and a 90% reduction lowered F_{contam} by 32%. A 90% decrease in F_N reduced the overall contamination rate from 12% to 8%. The change was not greater because the 7% contamination rate for daytime flights was unaffected by this mitigation.

Discussion

Arrivals of hitchhikers in cargo aircraft at MIA

Contamination rates were greatest, 23%, on cargo flights from C. Am. and much lower, near 5%, on flights from all other regions (PRMC

2000; Dobbs and Brodel 2004). From that, one might conclude that only C. Am. flights pose a significant threat for arrivals of hitchhiking insect pests at MIA. That would have underestimated the risk from S. Am. flights, however. Contamination rate is only one component of propagule pressure, so predicted arrivals better reflect the true risk of establishment. For this pathway, contamination rates may overestimate the risk if any of the following are true: (a) flight volumes are very low, (b) few of the pests are adults, or (c) few are females.

The use of pest risk classes further informed the results. Considering pest risk ratings, the greatest threats were from moderate-risk pests on flights from C. Am. and S. Am. In contrast, few arrivals of high-risk pests were predicted (Table 6). Critical threshold probabilities were relatively great, at least 3%, for high-risk pests, indicating a low likelihood of establishment. Even for classes with many more arrivals, such as moderate-risk pests from C. Am., it remains to be seen if actual p_{estab} values are as great as 0.002 (0.2%). We did not estimate the likelihood of establishment because it was not studied here and modeling those processes (Figure 1) would be difficult (Heger and Trepl 2003) and give uncertain results.

One mitigating factor in the pathway is that often only one pest per family arrived per flight (Figure 2). If most arriving female pests are not gravid, the difficulty in finding a compatible mate would greatly reduce the likelihood of successful establishment. Mating before dispersal is common for some insect families (S. Robertson, CPHST, pers. comm.), however, particularly

Lepidoptera (e.g., Chamberlain et al. 2000). Females in those families will likely enter cargo holds already gravid, and ready to oviposit upon arrival in Florida.

Significant differences by countries were not detected (not shown). An adequate sample size for a proportion is about 30 (Cochran 1977), and only eight countries met that standard. Although it might be more efficient to apply country-specific mitigation strategies (below), properly estimating country rates would have required a different sampling scheme. We think the study methodology was appropriate to a first, holistic assessment of the pathway.

For commodities, pests likely enter a pathway on or with a host. That is probably not true for this and other conveyance pathways. The simplest mechanism for entry here that explains the associations found is that insects entered cargo holds randomly while dispersing and remained on board, sometimes because certain cargo types were present. Contamination rates were greater for wet season C. Am. flights because insects were more locally abundant and therefore more likely to enter. The same was true for nighttime flights because loading operations attracted more insects to the aircraft, particularly nocturnal taxa or taxa attracted to light (Table 5). Furthermore, insect pests were very unlikely to arrive on empty aircraft, probably indicating that holds were inaccessible. Although difficult to assess, we found no good evidence that many hitchhikers dropped off of loaded cargo or were lured into holds by phytochemicals or aromas. Such sensory responses are limited by distance (e.g., Bernays and Chapman 1994) and would be further reduced by frequent wrapping of pallets in plastic.

Importance of the international cargo aircraft pathway at MIA

Pathway approach rates often vary and may have unique pest compositions. Comparing pathways is also difficult because pest risk and volume are critical but dynamic features of all pathways (Invasive Species Advisory Committee 2003). Risk enhancing factors for the cargo aircraft pathway are the speed of transport, climate-controlled conditions, and the potential presence of live plant products. The primary risk reducing

factors are that pests will probably not be associated with a host and may easily access the hold, biasing composition toward flying insects. By comparison, sea cargo containers make slower trips, are often not climate-controlled, and are unlikely to carry live plant products, but may be more accessible to insects and other pests and are more difficult to inspect.

Comparisons to other pathways at MIA are possible. From 2000 to 2003, approach rates for quarantine material interceptions (QMI) on passengers varied from a low of 4.7% in 2001 to a high of 9.4% in 2000 (USDA-APHIS-PPQ 2004b). When combined with data for international passenger arrivals (Miami International Airport 2004) the mean estimate of total potential QMI was 534,000. If one assumes a 1.4% infestation rate (Hawaii Department of Agriculture 2004), mean pest arrivals on passenger QMIs are about 7500 per year. Moreover, pests in baggage arrive on hosts which are sometimes brought specifically for propagation. Infested hosts on tropical flights often include ornamental plants, vegetables, and fruit, especially citrus (e.g., Miller 1997).

Also at MIA, over the same time period as this study, 3654 total quarantine-significant insects were intercepted on all aircraft (USDA-APHIS-PPQ 2004a) [numbers include interceptions from this study and are approximate because of possible problems in PIN-309]. The great majority of those insects, 92.4%, were intercepted in cargo, including passenger baggage (28%) and commodities (64%), such as cut flowers, fruit, and vegetables. Interceptions of hitchhikers in holds made up 4.1%. The percentages nationwide over the same period were similar: 95% of insects were intercepted on cargo and 3% were hitchhikers in both stores and holds. Of course, inspections for hitchhikers on cargo aircraft are not routine at most airports.

Within Florida, Thomas (2000) reported a doubling in percentage establishment (statewide) of insect pests from Asia during 1986–2000, compared to 1970–1989 data (Frank and McCoy 1992). From 1998 to 2000, mean cargo imports from Asia were only 1.3% of total imports at MIA (Bureau of Transportation Statistics 2003). Thus, recent patterns of invasion in Florida seem unlikely to be directly related to hitchhikers on

cargo aircraft. This is supported by findings at a Hawaiian airport that the greatest risk of introduction of nonindigenous pests was on imported agricultural commodities (Hawaii Department of Agriculture 2004). Commercial smuggling of prohibited animal and plant products may be the current primary pathway for insect pest establishments in Florida (Florida Pest Exclusion Advisory Committee 2001). Still, international cargo aircraft at MIA may be a significant pathway for invasion by moderate-risk insects from C. Am. and S. Am.

Quantitative comparisons to non-MIA cargo pathways are possible for West Indian aircraft, solid wood packing material (SWPM), sea cargo containers in Australia, and Mexican avocados. The West Indies differed greatly, as the contamination rate for all aircraft was 0.7%, and 83% of the insects were house flies (Le Maitre and Chadee 1983). An average of 402 insects per year were intercepted on SWPM nationwide from 1996 to 1998, but materials may arrive with over 250 different commodities, only a small percentage may be inspected, and detection is very difficult (USDA 2000), so actual arrivals are probably much greater. Coleoptera were 94% and Lepidoptera 2% of all interceptions on SWPM, while Coleoptera and Lepidoptera were both 35% of all interceptions on cargo aircraft at MIA. For sea cargo containers in Australia the mean contamination rate for exotic pests was about 3% (not given, ca. 100 out of 3001) (Stanaway et al. 2001). As with cargo aircraft, however, volume is important: about 1500 containers arrive per day. Last, CPHST (2004) estimated that on average 774 avocados infested with either fruit flies or other insects would arrive in the US per year from Mexico. That is much less than mean $N_{\text{tot}} = 3100$ on cargo aircraft at MIA. For these examples, the cargo aircraft pathway at MIA probably has moderate potential importance, below SWPM and above Mexican avocados, and probably less than sea cargo containers in Australia.

Possible mitigation strategies

Because most hitchhikers seemed to enter aircraft holds haphazardly, the best mitigation strategy for this pathway would be to reduce pest access

to holds. Some means for that are using slitted plastic covers or air barriers over hatches, or blowing insects out of holds with compressed air (Dobbs and Brodel 2004). Another option would be to close holds whenever possible (see above). A second strategy would be to reduce the number of insects near cargo aircraft during loading, which might be done by reducing the attractiveness of nighttime loading operations, removing nearby vegetation that may harbor pests, actively luring insects away from loading operations (Dobbs and Brodel 2004), or switching from nighttime to daytime flights. Departure times may be least effective, since simulations indicated that switching to daytime flights would only moderately reduce pest arrivals, and might be difficult to change for logistic or economic reasons. Reducing the attractiveness of nighttime loading operations may be particularly useful, and APHIS' International Services staff are working on that with airport managers in San José, Costa Rica (Gonzales 2003). Most flights depart there between 10:00 pm and 2:00 am local time. Measures being considered are using yellow instead of white light bulbs, placing traps in warehouses and on the tarmac near cargo, and placing traps to specifically attract lepidopterans. Whether these measures will be implemented and how much effect they may have on contamination rates remains to be seen.

The primary mitigation measure at MIA now, once flights have arrived, is officer inspections followed by treatment with pesticide if quarantine-significant pests are found. Inspection is only efficient for flights with greater contamination rates. For example, using inspections on flights from S. Am. seems untenable, since on average 25 flights would have to be inspected to find 1 female pest. In contrast, inspections may work well for flights from C. Am., since on average a female pest may be found every 3–6 flights, depending on the season. Inspections of all aircraft from C. Am. plus Ecuador and Mexico have been ongoing at MIA since May, 2002 (Martinez 2003). Still, optimizing inspections toward riskier flights, based on the cargo, seasonal, and diurnal associations detected above, may be more efficient than inspecting every flight. For example, managers might reasonably cease inspections of empty aircraft, or might, for dry season flights from C. Am., focus

inspections on nighttime flights containing either plant products or clothing. Further model analyses will test such optimization strategies.

Summary and conclusions

The PRMC (2000) study was a unique, well-done effort to better quantify and understand the risks posed by hitchhiking pests on the cargo aircraft pathway to Miami. Such comprehensive studies are increasingly needed (GAO 2002) and are particularly useful to risk managers and other interested parties. In particular, model results demonstrated that risk was better estimated by insect arrivals, which accounted for both flight volume and contamination (approach) rates which by themselves can be misleading. Arrivals of moderate-risk pests from C. Am. and S. Am. were most threatening and had uncomfortably low threshold probabilities of establishment (p_{crit}). The best mitigation strategies would reduce contamination at the origin and therefore are not controlled by pest risk managers at MIA. Inspections at MIA will probably only be useful for flights from C. Am. but can be optimized by targeting high risk path-

way factors (e.g., nighttime departure). In suitable habitats, propagule size (e.g., N_{tot} or N_{φ}) may strongly determine invasion success (Simberloff 1997), and South Florida is likely climatically acceptable for many of these pests. This pathway may be less risky than some other pathways at MIA but the risks still seem significant. Predicting likelihoods of establishment was not possible here and is generally very difficult (Simberloff 1997; Heger and Trepl 2003). Nevertheless, the understanding gained about cargo aircraft pathway processes from one quantitative study demonstrates the potential to evaluate and prioritize potentially important invasion pathways.

Acknowledgements

We thank the members of the PRMC and the USDA Miami Cargo Aircraft workgroup, PERAL scientists for their assistance and comments on drafts, and two anonymous reviewers for helpful comments and suggestions. We also thank Shawn Robertson of PERAL for his valuable technical help, and Calvin Shuler of the PPQ Eastern Region Office.

Appendix A. Reportable insect pests intercepted on international cargo aircraft arriving at Miami International Airport during the PRMC (2000) study, with taxonomic information, region and origin of the flight, number of pests intercepted, and the potential risk rating (high, moderate, or low) for that insect pest (see text).

Order	Family	Genus	Species	Authority	Region ¹	Origin	No. intercepted	Risk rating ²
Coleoptera	Chrysomelidae	<i>Acalymma</i>	sp.		Cent. Am.	Guatemala	1 ^b	Low
		<i>Acalymma</i>	sp.		South Am.	Ecuador	1 ^b	
		<i>Altica</i>	sp.		Cent. Am.	El Salvador	1 ^a	Low
		Alticinae	sp.		Cent. Am.	Mexico	1	Moderate
		<i>Amphelasma</i>	sp.		Cent. Am.	Honduras	1	Low
		<i>Colaspis</i>	sp.		Cent. Am.	El Salvador	1	Low
		<i>Colaspis</i>	sp.		Cent. Am.	Honduras	2	
		<i>Epitrix</i>	sp.		Cent. Am.	El Salvador	1 ^a	Moderate
		<i>Exora</i>	<i>encaustica</i>	(Germ.)	Cent. Am.	El Salvador	1	Low
		<i>Longitarsus</i>	sp.		South Am.	Ecuador	1 ^a	Moderate
		<i>Malacorhinus</i>	<i>irregularis</i>	(Jacoby)	Cent. Am.	El Salvador	1	Low
		<i>Metachroma</i>	sp.		Cent. Am.	Costa Rica	1 ^a	Low
		<i>Rhabdopterus</i>	sp.		Cent. Am.	Costa Rica	1 ^a	Moderate
		<i>Typophorus</i>	sp.		Cent. Am.	El Salvador	1 ^a	Low
	Curculionidae	sp.			Cent. Am.	El Salvador	1	Moderate
		Brachycerinae	sp.		Cent. Am.	El Salvador	1	Moderate
		<i>Cleogonus</i>	sp.		Cent. Am.	El Salvador	1 ^b	Moderate
		<i>Conotrachelus</i>	spp.		Cent. Am.	El Salvador	2 ^a	High

Appendix A. Continued.

Order	Family	Genus	Species	Authority	Region ¹	Origin	No. intercepted	Risk rating ²
Hemiptera	Elateridae	<i>Conoderus</i>	<i>pictus</i>	(Candeze)	Cent. Am.	El Salvador	1 ^b	Low
		<i>Conoderus</i>	<i>rodriguezi</i>	(Candeze)	Cent. Am.	Costa Rica	1	Low
		<i>Conoderus</i>	<i>rodriguezi</i>	(Candeze)	Cent. Am.	Guatemala	1	
	Scarabaeidae	Melolonthinae	sp.		South Am.	Ecuador	1	Moderate
		<i>Anomala</i>	spp.		Cent. Am.	Costa Rica	2	Moderate
		<i>Anomala</i>	spp.		Cent. Am.	Guatemala	2	
		<i>Anomala</i>	sp.		Cent. Am.	Honduras	1	
		<i>Anomala</i>	sp.		Cent. Am.	Nicaragua	1	
		<i>Anomala</i>	sp.		South Am.	Trinidad	1	Moderate
		<i>Cyclocephala</i>	sp.		Cent. Am.	El Salvador	1	Moderate
		<i>Cyclocephala</i>	sp.		Cent. Am.	Honduras	1	
		<i>Cyclocephala</i>	sp.		Cent. Am.	Panama	1	
		<i>Cyclocephala</i>	sp.		South Am.	Ecuador	1	
		<i>Diplotaxis</i>	sp.		Cent. Am.	Mexico	1 ^a	Low
		<i>Dyscinetus</i>	sp.		Other	Canada	1	Low
		<i>Euetheola</i>	<i>bidentata</i>	Burmeister	Cent. Am.	El Salvador	1 ^a	High
		<i>Liogenys</i>	<i>quadridens</i>	(Fab.)	South Am.	Ecuador	1	Low
		<i>Liogenys</i>	sp.		South Am.	Colombia	1	Low
		<i>Manopus</i>	sp.		South Am.	Colombia	1 ^a	Low
		<i>Phyllophaga</i>	spp.		Cent. Am.	Guatemala	6	Moderate
		<i>Phyllophaga</i>	sp.		South Am.	Colombia	1	
		<i>Tomarus</i>	sp.		Cent. Am.	El Salvador	1	Moderate
		<i>Tomarus</i>	spp.		Cent. Am.	Guatemala	3	
		<i>Tomarus</i>	sp.		South Am.	Trinidad	1	
	Tenebrionidae	<i>Blapstinus</i>	sp.		Cent. Am.	Costa Rica	1	Moderate
		<i>Blapstinus</i>	sp.		South Am.	Trinidad	1	
	–	spp.			Cent. Am.	Costa Rica	2	Low
	Cercopidae	<i>Prosapia</i>	sp.		Cent. Am.	Costa Rica	1	Low
		<i>Prosapia</i>	sp.		Cent. Am.	El Salvador	1	
	Cicadellidae	spp.			Cent. Am.	Honduras	2	Moderate
		<i>Chlorotettix</i>	sp.		Cent. Am.	Honduras	1	Low
		Dikraneurini	sp.		Cent. Am.	Panama	1	Moderate
		<i>Exitianus</i>	sp.		Cent. Am.	Honduras	1 ^b	Moderate
		<i>Graphocephala</i>	sp.		South Am.	Ecuador	1	Low
		<i>Haldorus</i>	sp.		Carib.	Haiti	1	Low
		<i>Tagosodes</i>	spp.		Cent. Am.	El Salvador	2	Moderate
		Typhlocybinae	sp.		Cent. Am.	Mexico	1	Low
		Cixiidae	sp.		Cent. Am.	Mexico	1	Moderate
		<i>Pintalia</i>	sp.		Cent. Am.	Honduras	1	Low
	Cydnidae	sp.			Cent. Am.	Guatemala	1	Low
	Miridae	Phylinae	sp.		South Am.	Ecuador	1	Moderate
		<i>Reuteroscopus</i>	sp.		Cent. Am.	Mexico	1 ^b	Low
		<i>Sixeonotus</i>	sp.		Cent. Am.	El Salvador	1 ^b	Low
		<i>Tropidosteptes</i>	sp.		Cent. Am.	Guatemala	1	Moderate
		<i>Tropidosteptes</i>	<i>chapingoensis</i>	C.&R.	South Am.	Colombia	1	Moderate
	Nogodinidae	<i>Bladina</i>	<i>vexans</i>	Kramer	South Am.	Colombia	1	Low
	Orsillidae	<i>Nysius</i>	sp.		Cent. Am.	Nicaragua	1 ^a	Moderate

Appendix A. Continued.

Order	Family	Genus	Species	Authority	Region ¹	Origin	No. intercepted	Risk rating ²
Isoptera	Pentatomidae	<i>Berecynthus</i>	<i>hastator</i>	(Fab.)	Cent. Am.	El Salvador	1 ^a	Low
	Rhopalidae	<i>Jadera</i>	sp.		Cent. Am.	Costa Rica	1 ^a	Low
	Rhyperochromidae	sp.			Cent. Am.	El Salvador	1	Moderate
		<i>Prytanes</i>	sp.		Cent. Am.	Guatemala	1	Low
	Kalotermitidae	<i>Cryptotermes</i>	sp.		Cent. Am.	Honduras	1 ^b	Low
	Lepidoptera	Arctiidae	sp.		South Am.	Colombia	1	Low
		<i>Empyreuma</i>	sp.		Carib.	Dominican Republic	1	Low
	Crambidae	sp.			Cent. Am.	Nicaragua	1	Moderate
		spp.			Cent. Am.	Costa Rica	2	
	Elachistidae	sp.			Cent. Am.	Costa Rica	1	Low
	Gelechiidae	sp.			Cent. Am.	Guatemala	1	Moderate
	Gelechioidea	sp.			Carib.	Dominican Republic	1	Moderate
	Geometridae	spp.			Cent. Am.	Costa Rica	4	Low
		spp.			Cent. Am.	Guatemala	3	
		sp.			Cent. Am.	Nicaragua	1	
		sp.			Cent. Am.	Panama	1	
		sp.			South Am.	Ecuador	1	
		<i>Eupithecia</i>	sp.		Cent. Am.	Guatemala	1 ^b	Moderate
	Gracillariidae	<i>Phyllocnistis</i>	sp.		South Am.	Colombia	1	Moderate
	Noctuidae	sp.			Carib.	Haiti	1	Moderate
		spp.			Cent. Am.	Costa Rica	5	
		spp.			Cent. Am.	Guatemala	3	
		spp.			Cent. Am.	Honduras	2	
		sp.			Cent. Am.	Mexico	1	
		spp.			Cent. Am.	Nicaragua	5	
		sp.			South Am.	Panama	1	
		Catocalinae	sp.		Cent. Am.	Costa Rica	1	Low
		Catocalinae	sp.		Cent. Am.	Mexico	1	
		<i>Copitarsia</i>	sp.		South Am.	Colombia	1	High
		<i>Elaphria</i>	sp.		Cent. Am.	Costa Rica	1	Moderate
		<i>Eulepidotis</i>	<i>mabis</i>	Guenee	Cent. Am.	Costa Rica	1	Moderate
Orthoptera		<i>Ophisma</i>	sp.		Cent. Am.	Nicaragua	1	Low
		<i>Pararcte</i>	<i>schneideriana</i>	(Stoll)	South Am.	Ecuador	1	Low
		<i>Phalaenophana</i>	<i>Fadusalis</i>	Walker	Cent. Am.	Costa Rica	1	Low
	Notodontidae	sp.			Cent. Am.	Costa Rica	1	Low
	Oecophoridae	sp.			Cent. Am.	Costa Rica	1	Low
	Pyalidae	spp.			Cent. Am.	El Salvador	2	Moderate
		sp.			South Am.	Peru	1	
	Pyaloidae	sp.			Cent. Am.	Guatemala	1	Moderate
	Sphingidae	sp.			South Am.	Venezuela	1	Low
	Tineidae	Acrolophinae	sp.		South Am.	Colombia	1	Low
	Tortricidae	<i>Crociosema</i>	<i>aporema</i>	(Walsingham)	Cent. Am.	Guatemala	1 ^b	High
	Gryllidae	sp.			Cent. Am.	Costa Rica	1	Low
		<i>Allonemobius</i>	sp.		Cent. Am.	Honduras	1 ^b	Low
		<i>Gryllus</i>	<i>capitatus</i>	Saussure	South Am.	Ecuador	2	Low
		<i>Gryllus</i>	sp.		Carib.	Jamaica	1	Low

Appendix A. Continued.

Order	Family	Genus	Species	Authority	Region ¹	Origin	No. intercepted	Risk rating ²
		<i>Gryllus</i>	spp.		Cent. Am.	Costa Rica	2	
		<i>Gryllus</i>	spp.		Cent. Am.	Guatemala	2	
		<i>Gryllus</i>	spp.		Cent. Am.	Honduras	3	
		<i>Gryllus</i>	sp.		South Am.	Colombia	1	
	Tetrigidae	<i>Tettigidea</i>	sp.		Cent. Am.	El Salvador	1	Low
	Tettigoniidae	sp.			Cent. Am.	Costa Rica	1	Low
		sp.			Cent. Am.	Honduras	1	
		<i>Bucrates</i>	<i>capitatus</i>	(DeGeer)	South Am	Colombia	1	Low
		<i>Conocephalus</i>	sp.		Cent. Am.	Honduras	1	Low
		<i>Neoconocephalus</i>	<i>punctipes</i>	(Redtenbacher)	Cent. Am.	El Salvador	1	Low

¹Regions were Carib. = Caribbean, Cent. Am. = Central America, South Am. = South America, and Other = other places.

²Rating is given only for the first instance of each taxa.

^aFirst interception of this taxon in aircraft at MIA.

^bFirst interception of this taxon in aircraft in both the U.S.A. and at MIA.

Appendix B. Base spreadsheet model for predicting arrivals of hitchhiking female pests at Miami International Airport on international cargo aircraft from three regions, South America (SA), the Caribbean (Carib), and all other regions (Other). Formulae show functions for the first cell in the range. All calculated cell values are output; examples are sampled values for one iteration. Legend: shaded boxes are input values or parameters, and double lines indicate probabilistic functions.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1		SA	Carib	Other								row	bins	SA	Carib	Other
2	Flights per year	12129	2337	1275			All					2	650	0	0	0
3	Flights per month	1011	195	106		months	12					3	700	0	0	2
4							SA	Carib	Other			4	750	0	0	40
5	Contaminated flts per year	699	94	85		s	19	4	1			5	800	0	0	165
6	Contaminated flts per month	58	8	7		n	345	122	28			6	850	0	0	270
7							SA	Carib				7	900	0	0	303
8	Insect pests per year	993	118	85		mn	1.42	1.25				8	950	0	0	249
9	Insect pests per contam flight	1.4	1.3	1.0		sd	0.607	0.5				9	1000	0	0	210
10							All					10	1050	0	0	227
11	Adult insects per year	974	116	83		s	156					11	1100	0	0	324
12	Adults per month	81	10	7		n	158					12	1150	0	0	410
13												13	1200	0	0	440
14	Females per year	487	58	42		p female	0.50					14	1250	0	0	339
15	Females per month	40.6	4.8	3.5								15	1300	0	1	232
16	Females per day	1.33	0.16	0.12		days	365					16	1350	0	13	189
17	Females per contam flight	0.70	0.62	0.49								17	1400	0	56	177
18	Females per flight	0.04	0.02	0.03								18	1450	0	115	191
19												19	1500	0	184	166
20	Cell range	Formulae														
21	B2:D2	=ROUND(RiskHistogram(\$M\$2,\$M\$279,N2:N279),0)														
22	B3:D3,B6:D6,B12:D12,B15:D15	=B2/\$G\$3														
23	B5:D5	=B2*RiskBeta(G5+1,G6-G5+1)														
24	B8:C8	=ROUND(RiskNormal(B\$5*G8,SQRT(B\$5)*G9),0)														
25	D8	=D5														
26	B9:D9	=IF(B5=0,0,B8/B5)														
27	B11:D11	=IF(B8=0,0,ROUND((B8*RiskBeta(\$G\$11+1,\$G\$12-\$G\$11+1)),0))														
28	B14:D14	=IF(B11=0,0,RiskBinomial(B11,\$G\$14))														
29	B16:D16	=B14/\$G\$16														
30	B17:D17	=IF(B5=0,0,B14/B5)														
31	B18:D18	=IF(B2=0,0,B14/B2)														
32	M2:P279	Submodel output														
33	G5:I6,G8:H9,G11:G12	Empirical data tables														
34	G3,G14,G16	Parameter values														
35													277	14400	1	0
													278	14450	0	0
													279	14500	1	0

References

- Bernays EA and Chapman RF (1994) Host-Plant Selection by Phytophagous Insects. Chapman & Hall, New York, 312 pp
- Borror DJ, Triplehorn CA and Johnson NF (1989) An Introduction to the Study of Insects. 6th ed. Saunders College Pub, Philadelphia, 875 pp
- Bureau of Transportation Statistics. 2003. Large Air Carrier Statistics (Form 41 Traffic) [Online]. Department of Transportation <http://www.transtats.bts.gov/> (verified March 3, 2003)
- Chamberlain DJ, Brown NJ, Jones OT and Casagrande E (2000) Field evaluation of a slow release pheromone formulation to control the American bollworm, *Helicoverpa armigera* (Lepidoptera: Noctuidae) in Pakistan. Bulletin of Entomological Research 90: 183–190
- Clark S (1997) Chrysomelidae of Rio Bravo Conservation and Management Area, Belize [Online]. Louisiana State Arthropod Museum <http://www.agctr.lsu.edu/Inst/research/departments/arthropodmuseum/riobravo%20chrysomelidae.htm> (verified March 5, 2003)
- Cochran WG (1977) Sampling Techniques. 3rd ed. Wiley, New York, 428 pp
- CPHST (2004) Importation of Avocado Fruit (*Persea americana* Mill. var. 'Hass') from Mexico: A Risk Assessment. Center for Plant Health Science and Technology (CPHST), USDA-APHIS-PPQ, Raleigh, NC. May 24, 2004. 126 pp
- Dobbs TT and Brodel CF (2004) Cargo aircraft as a pathway for the entry of nonindigenous pests into South Florida. Florida Entomologist 87: 65–78
- FAO (2002) Glossary of Phytosanitary Terms, Publication No. 5. Secretariat of the International Plant Protection Convention, Food and Agriculture Organization (FAO) of the United Nations, Rome, Italy. April. 76 pp
- Florida Pest Exclusion Advisory Committee (2001) Pest Exclusion Advisory Committee Report. Florida Department of Agriculture & Consumer Services, Tallahassee FL. March 2001. 79 pp
- Frank JH and McCoy ED (1992) Introduction to the behavioral ecology of immigration. The immigration of insects of Florida, with a tabulation of records published since 1970. Florida Entomologist 75: 1–28
- Frank JH and McCoy ED (1995) Introduction to insect behavioral ecology: The good, the bad, and the beautiful: Non-indigenous species in Florida. Invasive adventive insects and other organisms in Florida. Florida Entomologist 78: 1–15
- GAO (2002) Invasive Species: Clearer Focus and Greater Commitment Needed to Effectively Manage the Problem, GAO-03-1. United States General Accounting Office (GAO), Washington, DC October 2002. 109 pp
- Gomez LD, Godoy JC, Herrera-MacBryde O, Villa-Lobos J (2003) Overview for Central America [Online]. Department of Botany, Smithsonian Institution, Washington DC <http://www.nmnh.si.edu/botany/projects/cpd/ma/macentral.htm#Climate> (verified April 23)
- Gonzales MV (2003) Report on the Evaluation of Cargo Areas and Cargo Airplanes. International Services, USDA-APHIS, San Jose, Costa Rica. June 2003. 3 pp
- Hawaii Department of Agriculture (2004) Kahului Airport Pest Risk Assessment. Plant Quarantine Branch, Hawaii Department of Agriculture, Honolulu, HI. November 2002. 41 pp
- Heger T and Trepl L (2003) Predicting biological invasions. Biological Invasions 5: 313–321
- Invasive Species Advisory Committee (2003) Invasive Species Pathways Team Final Report. Pathways Task Team, Invasive Species Advisory Committee, National Invasive Species Council, Department of the Interior, Washington, DC. October 29, 2003. 25 pp
- Knapp JL (1998) The Mediterranean Fruit Fly, ENY-809 [Online]. Entomology and Nematology Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida http://edis.ifas.ufl.edu/BODY_CH040 (verified August 26)
- Le Maitre A and Chadee DD (1983) Arthropods collected from aircraft at Piarco International Airport, Trinidad, West Indies. Mosquito News 43: 21–23
- Martinez R (2003) Aircraft cargo inspections update. USDA-APHIS-PPQ, Miami, Florida
- Miami International Airport (2004) Airport Statistics [Online]. Miami-Dade County http://www.miami-airport.com/html/airport_statistics_.html (verified June 21)
- Miller CE (1997) Evaluation of San Juan Predeparture Interceptions in Baggage (FY 1994–96) [Online]. Risk Analysis Systems, Plant Protection and Quarantine, Animal and Plant Health Inspections Service, US Department of Agriculture <http://www.aphis.usda.gov/ppq/pracommodity/hazardsanjuan.html> (verified June 21)
- Montoya GC, Madrigal CA and Ramirez CA (1994) Evaluation of light traps for the control of adult scarabaeids (Coleoptera) in potato crops in La Union (Antioquia) [Spanish]. Revista Colombiana de Entomologia 20: 130–136
- National Research Council (2002) Predicting Invasions of Nonindigenous Plants and Plant Pests. National Academy Press, Washington, DC 194 pp
- Office of Technology Assessment (1993) Harmful Non-Indigenous Species in the United States, OTA-F-565. US Congress, US Government Printing Office, Washington, DC September. 391 pp
- Olkin I, Gleser LJ and Derman C (1994) Probability models and applications. 2nd ed. Macmillan, New York, 715 pp
- PRMC (2000) Cargo Aircraft as a Pathway of Exotic Pest Introduction into South Florida. Pest Risk Management Committee, USDA-APHIS-PPQ, Miami, FL. March 9, 2000. 20 pp
- Program and Policy Development (1983) Proposal for Cut Flower Inspection Guidelines. PPD, USDA-APHIS-PPQ, Washington, DC. 13 pp
- Quade A (2003) Annual Cargo Aircraft Landings from 1997 to 2002. Marketing Division, Miami International Airport, Miami, Florida
- SAS Institute Inc. 2001. The SAS System for Windows. Release 8.02. SAS Institute Inc., Cary, NC
- Simberloff D (1997) The biology of invasions. In: Simberloff D, Schmitz DC and Brown TC (eds) Strangers in Paradise: Impacts and Management of Nonindigenous Species in Florida, pp 3–17. Island Press, Washington DC

- Stanaway MA, Zalucki MP, Gillespie PS, Rodriguez CM and Maynard GV (2001) Pest risk assessment of insects in sea cargo containers. *Australian Journal of Entomology* 40: 180–192
- Takahashi S (1984) Survey on accidental introductions of insects entering Japan via aircraft. In: Laird M. (ed) *Commerce and the Spread of Pests and Disease Vectors*, pp 65–80. Praeger, New York
- Thomas MC (2000) The Exotic Invasion of Florida: A Report on Arthropod Immigration into the Sunshine State [Online]. Florida State Collection of Arthropods <http://doacs.state.fl.us/~pi/enpp/ento/exoticsinflorida.htm> (verified March 4, 2003)
- USDA (2000) Pest Risk Assessment for Importation of Solid Wood Packing Materials into the United States. Animal and Plant Health Inspection Service, and Forest Service, United States Department of Agriculture (USDA), Washington, DC. August 2000. 275 pp
- USDA–APHIS–PPQ (2004a) Pest interception network (PIN309) [Online]. Plant Protection and Quarantine, Animal and Plant Health Inspection Service, US Department of Agriculture Washington, DC
- USDA–APHIS–PPQ (2004b) Quarantine material interceptions. Agricultural Quarantine Inspection Monitoring, Plant Protection and Quarantine, Animal and Plant Health Inspection Service, US Department of Agriculture, Washington, DC
- Vose D (2000) *Risk Analysis: A Quantitative Guide*. 2nd ed. John Wiley & Sons Ltd., New York, 418 pp
- Vose D (2003) *Animal Agriculture and Food Safety Risk Analysis Training*. Knoxville, TN
- World Meteorological Organization (2003) World Weather Information Service: North and Central America [Online]. World Meteorological Organization, Geneva, Switzerland http://www.worldweather.org/n_america.htm (verified April 25)